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<b>14. ABSTRACT</b>  <p>This report results from a contract tasking Crystal Fibre A/S as follows: Crystal Fibre will conduct research and development of large mode area, dual clad multi-core Yb-doped photonic crystal fiber. The fiber may be polarization maintaining (PM). Nominal fiber designs will include six and seven core fibers with nominal specifications of 400 micron 0.6 NA pump core, and 30-35 micron signal cores. Crystal Fibre shall fabricate 1 pre-form worth but not less than 50 meters of passive and active versions of each fiber designed under this task. Crystal Fibre shall provide characteristics of the fiber fabricated to include core and cladding diameters, core and cladding numerical apertures, Yb doping concentration, and pump absorption at 976nm. Passive multicore fiber versions without airclad will be available approximately 1½ month after fiber design agreement. Active multicore airclad fiber versions will be available approximately 3 months after fiber design agreement. Within this project we will deliver a passive and active version of multicore fiber iteration 1 and a passive version of multicore fiber iteration 2.</p>					
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# FINAL REPORT ITEM 0006

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## INTRODUCTION

This report describes the photonic crystal fibers developed under agreement No FA8655-05-1-3046. All information in this report is approved for public release with unlimited distribution.

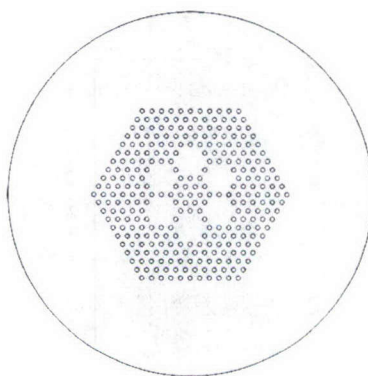
The following six fiber types are included in this report:

- Passive 6-core fiber
- Passive 7-core fiber
- Active Yb-doped 6-core airclad fiber
- Active Yb-doped 7-core airclad fiber
- Passive polarizing fiber
- Active Yb-doped polarizing air-clad fiber

Each fiber type is described separately in the following paragraphs and fiber specifications are listed for finalized fibers.

## PASSIVE 6-CORE FIBER

The fiber designed for this part of the project is a passive pure silica 6-core fiber. The fiber structure is shown schematically in Figure 1 below.



**Figure 1** Schematic of the fiber design. Gray denotes pure silica areas, white denotes air. Please note that the fiber cross-section is not drawn to scale.

Targets for the structural dimensions and optical properties can be found in the subsequent section.

## PHYSICAL PROPERTIES

The physical properties and structural dimensions of the fibers are listed below. Values listed in the "Fiber" column are measured values on the fabricated fiber. Values listed in the "Target" column are the design targets.

	<i>Fiber</i>	<i>Target</i>
<b>Material</b>		
Core material:	Pure silica	
Cladding material:	Pure silica	
Coating material:	Acrylate (single layer)	
<b>Dimensions, Fiber 1</b>		
Pitch:	10 $\mu\text{m}$	10 $\mu\text{m}$
Relative hole size:	0.176	0.18
Cladding diameter:	590 $\mu\text{m}$	~600 $\mu\text{m}$
Coating diameter:	715 $\mu\text{m}$	-



***Dimensions, Fiber 2***

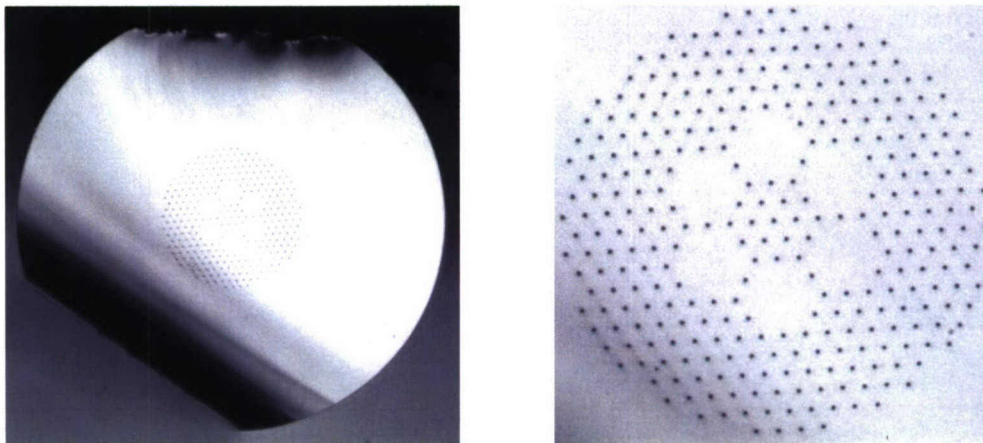
Pitch:	10 $\mu\text{m}$	10 $\mu\text{m}$
Relative hole size:	0.20	0.20
Cladding diameter:	590 $\mu\text{m}$	~600 $\mu\text{m}$
Coating diameter:	715 $\mu\text{m}$	-

***Dimensions, Fiber 3***

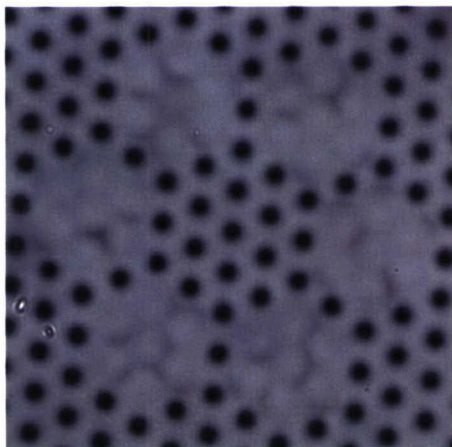
Pitch:	10 $\mu\text{m}$	10 $\mu\text{m}$
Relative hole size:	0.225	0.22
Cladding diameter:	590 $\mu\text{m}$	~600 $\mu\text{m}$
Coating diameter:	715 $\mu\text{m}$	-

<sup>1</sup>: Measured as diameter of the largest inscribed circle within the inner cladding layer.

***FIBER STRUCTURE***



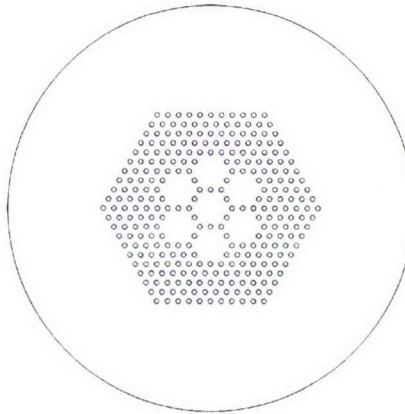
**Figure 2** Top illuminated microscope pictures of the entire fiber cross section and the microstructured region.



**Figure 3** Bottom illuminated microscope picture of the microstructured part of the fiber. The dark regions in the core are low-index areas formed by the outer part of the rods used to create the core. This kind of low index regions has not been observed in a fiber before and originate from the raw glass. The glass manufacturer has been notified and the origin of the low index is being investigated. It was mutually agreed that no redrawing of the fibers was needed.

## PASSIVE 7-CORE FIBER

The fiber designed for this part of the project is a passive pure silica 7-core fiber. The fiber structure is shown schematically in Figure 4 below.



**Figure 4** Schematic of the fiber design. Gray denotes pure silica areas, white denotes air. Please note that the fiber cross-section is not drawn to scale.

Targets for the structural dimensions and optical properties can be found in the subsequent section.

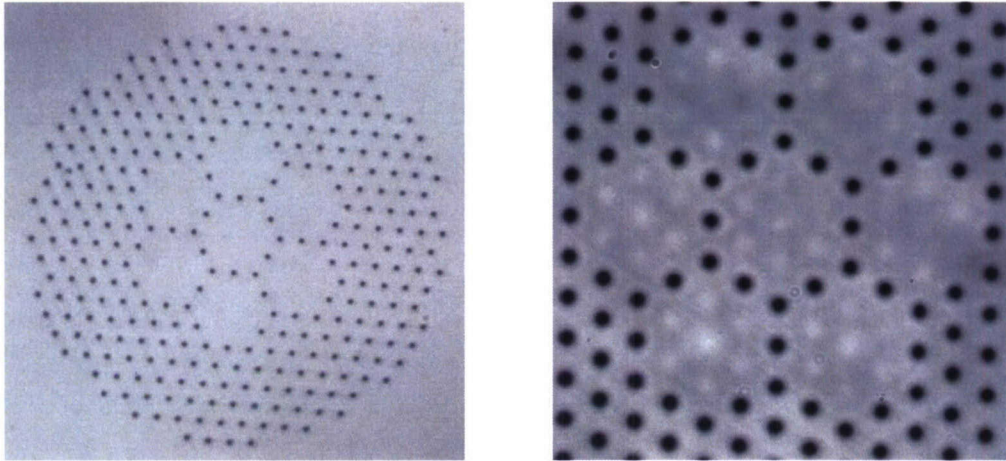
### PHYSICAL PROPERTIES

The physical properties and structural dimensions of the fibers are listed below. Values listed in the “Fiber” column are measured values on the fabricated fiber. Values listed in the “Target” column are the design targets.

	<i>Fiber</i>	<i>Target</i>
<b>Material</b>		
Core material:	Pure silica	
Cladding material:	Pure silica	
Coating material:	Acrylate (single layer)	
<b>Dimensions, Fiber 1</b>		
Pitch:	10.05 $\mu\text{m}$	10 $\mu\text{m}$
Relative hole size:	0.177	0.18
Cladding diameter:	593 $\mu\text{m}$	~600 $\mu\text{m}$
Coating diameter:	714 $\mu\text{m}$	-
<b>Dimensions, Fiber 2</b>		
Pitch:	10.1 $\mu\text{m}$	10 $\mu\text{m}$
Relative hole size:	0.197	0.20
Cladding diameter:	592 $\mu\text{m}$	~600 $\mu\text{m}$
Coating diameter:	714 $\mu\text{m}$	-
<b>Dimensions, Fiber 3</b>		
Pitch:	10.1 $\mu\text{m}$	10 $\mu\text{m}$
Relative hole size:	0.212	0.22
Cladding diameter:	587 $\mu\text{m}$	~600 $\mu\text{m}$
Coating diameter:	714 $\mu\text{m}$	-

<sup>1</sup>: Measured as diameter of the largest inscribed circle within the inner cladding layer.

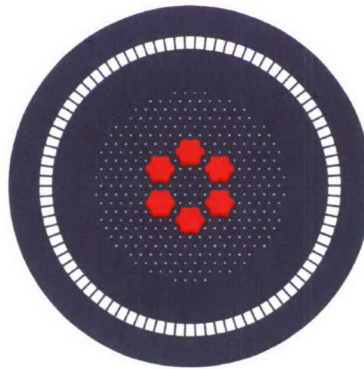
## FIBER STRUCTURE



**Figure 5** Top illuminated (left) and bottom illuminated (right) microscope pictures of the micro-structured region.

## ACTIVE 6-CORE FIBER

The fiber designed for this part of the project is an active Ytterbium-doped, 6-core fiber equipped with a high NA air-clad multimode pump-guide. The fiber structure is shown schematically in Figure 6 below.



**Figure 6** Schematic of the fiber design. Dark gray denotes pure silica areas, white denotes air and the six ytterbium doped cores are shown in red. Please note that the fiber cross-section is not drawn to scale.

Targets for the structural dimensions and optical properties can be found in the subsequent section.

## PHYSICAL PROPERTIES

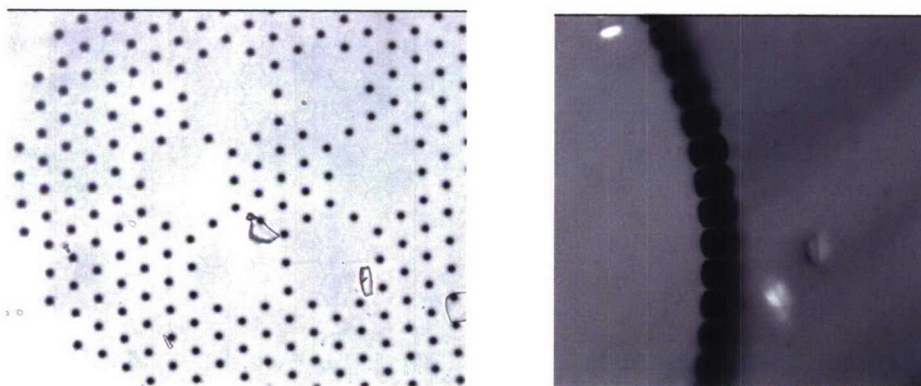
The physical properties and structural dimensions of the fibers are listed below. Values listed in the “Fiber” column are measured values on the fabricated fiber. Values listed in the “Target” column are the design targets.



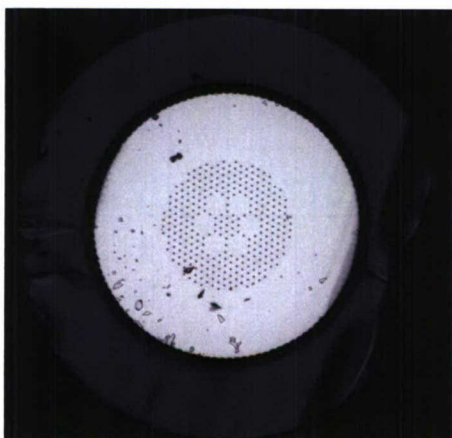
	<i>Fiber</i>	<i>Target</i>
<b>Material</b>		
Core material:	Yb-doped silica	
Cladding material:	Pure silica	
Coating material:	High temperature acrylate (single layer)	
<b>Dimensions</b>		
Pitch:	10.0 $\mu\text{m}$	10 $\mu\text{m}$
Relative hole size:	0.195	0.2
Core diameter:	38 $\mu\text{m}$	38 $\mu\text{m}$
Cladding diameter:	635 $\mu\text{m}$	~600 $\mu\text{m}$
Coating diameter:	800 $\mu\text{m}$	~700 $\mu\text{m}$
<b>Air-cladding dimensions</b>		
Length of silica bridges:	15-16 $\mu\text{m}$	~15 $\mu\text{m}$
Inner diameter <sup>1</sup> :	399	380 $\mu\text{m}$
<b>Optical Properties</b>		
Pump absorption at 976 nm:	-	10-15 dB/m
Air-cladding NA	0.56	~0.6

<sup>1</sup>: Measured as diameter of the largest inscribed circle within the inner cladding layer.

#### FIBER STRUCTURE



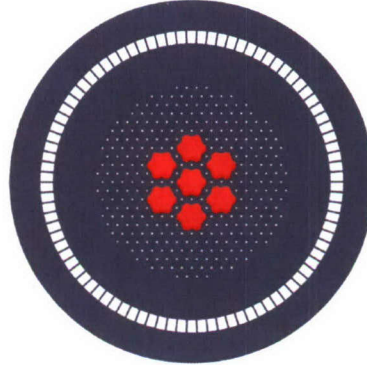
**Figure 7** Microscope pictures of (left) the six Yb-doped inner cores, and (right) the air-clad.



**Figure 8** Microscope pictures of the entire fiber cross section. The fiber is illuminated from below.

## ACTIVE 7-CORE FIBER

The fiber designed for this part of the project is an active Ytterbium-doped, 7-core fiber equipped with a high NA air-clad multimode pump-guide. The fiber structure is shown schematically in Figure 9 below.



**Figure 9** Schematic of the fiber design. Dark gray denotes pure silica areas, white denotes air and the seven ytterbium doped cores are shown in red. Please note that the fiber cross-section is not drawn to scale.

Targets for the structural dimensions and optical properties can be found in the subsequent section.

### PHYSICAL PROPERTIES

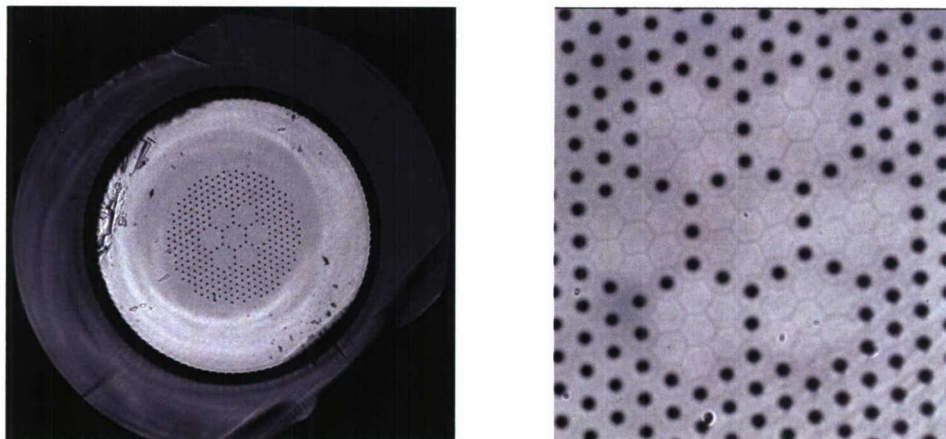
The physical properties and structural dimensions of the fibers are listed below. Values listed in the “Fiber” column are measured values on the fabricated fiber. Values listed in the “Target” column are the design targets.

	<i>Fiber</i>	<i>Target</i>
<b>Material</b>		
Core material:	Yb-doped silica	
Cladding material:	Pure silica	
Coating material:	High temperature acrylate (single layer)	
<b>Dimensions</b>		
Pitch:	10 μm	10 μm
Relative hole size:	0.2-0.22	0.2
Core diameter:	38 μm	38 μm
Cladding diameter:	650 μm	~600 μm
Coating diameter:	820 μm	~700 μm
<b>Air-cladding dimensions</b>		
Inner diameter <sup>1</sup>	404 μm	380 μm
<b>Optical Properties</b>		
Pump absorption at 976 nm:	-	10-15 dB/m
Air-cladding NA	0.55	~0.6

<sup>1</sup> : Measured as diameter of the largest inscribed circle within the inner cladding layer.



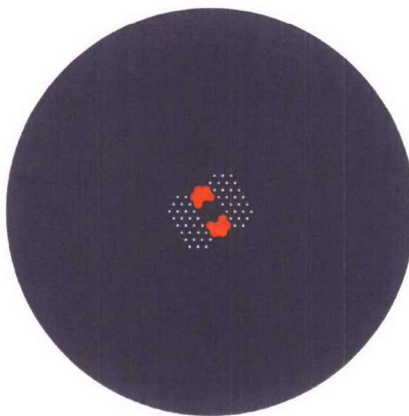
## FIBER STRUCTURE



**Figure 10** Microscope pictures of the entire fiber cross section (left). And the 7 active Yb-doped cores (right). The fiber is illuminated from below.

## PASSIVE POLARIZING FIBER

The fiber designed for this part of the project is a pure silica, polarizing large-mode area fiber. The fiber structure is shown schematically in Figure 11 below.



**Figure 11** Schematic of the fiber design. Dark gray denotes pure silica areas, white denotes air. The polarizing properties are obtained using stress inducing elements (shown in orange). Please note that the fiber cross-section is not drawn to scale.

Targets for the structural dimensions and optical properties can be found in the subsequent section.

This fiber is scheduled for delivery primo 2006.

## FIBER DESIGN TARGETS

### Material

Core material:  
Cladding material:  
Coating material:

Pure silica  
Pure silica  
High temperature acrylate (single layer)

### *Dimensions*

Pitch:	10 $\mu\text{m}$
Relative hole size:	0.2
Core diameter:	38 $\mu\text{m}$
Cladding diameter:	$\sim 600 \mu\text{m}$
Coating diameter:	$\sim 700 \mu\text{m}$

### *Air-cladding dimensions*

Number of silica bridges:	120
Thickness of silica bridges:	$\sim 0.4 \mu\text{m}$
Length of silica bridges:	$\sim 15 \mu\text{m}$
Inner diameter <sup>1</sup>	380 $\mu\text{m}$

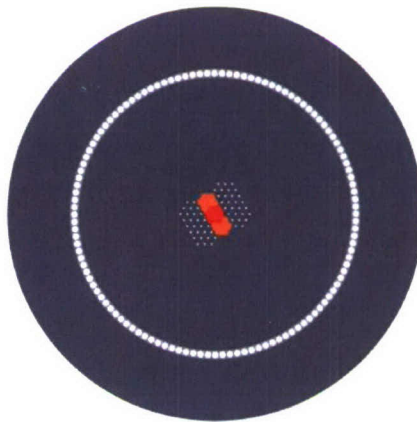
### *Optical Properties*

Birefringence:	$> 1 \cdot 10^{-4}$
Polarizing bandwidth:	$> 100 \text{ nm}$
PZ center wavelength	1 $\mu\text{m}$

<sup>1</sup> : Measured as diameter of the largest inscribed circle within the inner cladding layer.

## ACTIVE POLARIZING FIBER

The fiber designed for this part of the project is an active Ytterbium-doped, polarizing large-mode area fiber equipped with a high NA air-clad multimode pump-guide. The fiber structure is shown schematically in Figure 12 below.



**Figure 12** Schematic of the fiber design. Dark gray denotes pure silica areas, white denotes air and the ytterbium-doped core is shown in red. The polarizing properties are obtained using stress inducing elements (shown in orange). Please note that the fiber cross-section is not drawn to scale.

Targets for the structural dimensions and optical properties can be found in the subsequent section.

This fiber is scheduled for delivery primo 2006.

### *FIBER DESIGN TARGETS*

#### *Material*

Core material:	Yb-doped silica
Cladding material:	Pure silica
Coating material:	High temperature acrylate (single layer)

***Dimensions***

Pitch:	10 $\mu\text{m}$
Relative hole size:	0.2
Core diameter:	38 $\mu\text{m}$
Cladding diameter:	$\sim 600 \mu\text{m}$
Coating diameter:	$\sim 700 \mu\text{m}$

***Air-cladding dimensions***

Number of silica bridges:	120
Thickness of silica bridges:	$\sim 0.4 \mu\text{m}$
Length of silica bridges:	$\sim 15 \mu\text{m}$
Inner diameter <sup>1</sup>	380 $\mu\text{m}$

***Optical Properties***

Pump absorption at 976 nm:	$\sim 2.5 \text{ dB/m}$
Air-cladding NA:	$\sim 0.6$
Birefringence:	$> 1 \cdot 10^{-4}$
Polarizing bandwidth:	$> 100 \text{ nm}$
PZ center wavelength	1 $\mu\text{m}$

<sup>1</sup>: Measured as diameter of the largest inscribed circle within the inner cladding layer.

We certify that there were no subject inventions to declare during the performance of this grant.



Kim P. Hansen



Jes Broeng